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LONGITUDINAL VORTICES IN A TRANSITIONING BOUNDARY LAYER

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Longitudinal Vortices in a Transitioning Boundary Layer

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Summary

Naturally occurring spanwise variations of the streamwise velocity component, characteristic of longitudinal vortices embedded in a transitioning boundary layer were explored using hot-wire anemometers. A vibrating ribbon introduced stable or unstable Tollmien-Schlichting waves into the laminar boundary layer. These damped or growing disturbances always developed a strong three-dimensional pattern even though no spanwise perturbations were artificially induced. Changing the radius of the leading edge and other modifications to the flat plate, wind tunnel and boundary layer did not alter the spanwise wavelength of the vortices.

Introduction

Although the linear growth of two-dimensional Tollmien-Schlichting waves is reasonably well understood, Klebanoff, Tidstrom and Sargent [1] have shown that these waves rapidly develop a three-dimensional structure. Their detailed experimental measurements, as well as those of Kovasznay, Komoda and Vasudeva [2], showed that the developing structure was consistent with a spanwise system of counter-rotating longitudinal vortices within the boundary layer. This three-dimensional structure has been noted by several subsequent investigators; however, its origin remains unclear. The present investigation was undertaken to explore this particular aspect of transition. Among the factors considered potentially important were those affecting the tunnel free-stream properties (screens, honeycomb, free-stream velocity), those affecting the test model (leading edge diameter, surface condition, ribbon position) and those affecting mainly the boundary layer instability (Tollmien-Schlichting frequency, Reynolds number, ribbon amplitude). All of these factors have been investigated to some degree in the present experiment. The spanwise structure in the boundary layer may be influenced by other parameters which could not be varied in this experiment. The Gortler vortex system which forms in the boundary layer of the contraction section may cause minute variations in the test sections. Similarly, small perturbations from the wakes of turning vanes may be present even though they are damped by the screens. However, they probably are not the general cause of the spanwise inhomogeneity since the tunnel used by Kovasznay et al. [2] had none. Small spanwise variations in the stagnation line may be present with an unknown effect on the spanwise structure. In this experiment, the

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stagnation point was positioned by adjusting a trailing edge flap. Small tufts placed around the leading edge indicated the stagnation point was on the working surface. Small perturbations in leading edge geometry were studied by using spanwise strips of cellophane tape. No significant variations in the three-dimensional pattern downstream were observed.

Apparatus and tests

A highly polished 12 ft. (366 cm) long flat plate was mounted in the University of Southern California Low-Speed Wind Tunnel previously described by Wygnanski, Haritonidis and Kaplan [3]. The zero pressure gradient test section has a free-stream turbulence level of 0.03%. The plate had two interchangeable leading edges of 0.25 in. (0.635 cm) and 2 in. (5.08 cm) diameters. Two-dimensional disturbances were introduced into the laminar boundary layer by a 0.060 in. (15 mm) wide and .002 in. (.05 mm) thick tantalum ribbon mounted spanwise on the plate at a height of 0.010 in. (0.25 mm) from the surface. The ribbon was located 6 in. (15.2 cm) downstream of the 0.25 in. leading edge and 8 in. downstream of the 2.0 in. leading edge. The unsupported span of the ribbon was approximately 16 in. (40 cm). Two permanent magnets were mounted on the reverse side of the plate to provide a magnetic field and an alternating current through the ribbon caused single mode vibration at the desired frequency. The streamwise coordinate is x, the normal coordinate is y and the spanwise direction is denoted by z. The position downstream of the ribbon is given by x_1.

The streamwise velocity was measured by two methods. A highly streamlined, spanwise rake of twelve 0.030 in. (0.75 mm) long hot-wires separated by 0.030 in (0.75 mm) was used to obtain simultaneous streamwise velocity signals in the boundary layer. A single hot-wire mounted on a sled was utilized to continously traverse the flow field over a large spanwise and streamwise distance. Both techniques maintained a constant y/δ at all spanwise positions and were used at many streamwise positions downstream of the ribbon. The data were digitized and processed on-line by a DEC 11T55 computer and the resultant data were simultaneously plotted on a Tektronix 4010 graphics terminal.

Figure 1 shows the placement of the ribbon relative to the stability diagram for a flat plate. The 2 in. (5.08 cm) diameter leading edge increased the plate length ahead of the ribbon by 2 in. (5 cm), hence, the ribbon operated in a slightly more or less amplified region for the large leading edge tests depending on the frequency used. Typical measurement stations downstream are indicated as well as the ribbon locations for the tests of Klebanoff, et al. [1] and Kovasznay, et al. [2]. However, unlike the measurements of Klebahoff and Kovasznay, the majority of the present data were taken without the influence of cellophane tape strips on the plate surface. Therefore, the three-dimensional pattern of the present experiment developed naturally within the bounds of the apparatus.

Results and discussion

Earlier results of Klebanoff and Tidstrom [4] showed that when disturbed by a two-dimensional perturbation, the spanwise pattern which developed in the laminar boundary layer was influenced by the settling chamber screens. This suggests that the small residual vorticity in the free-stream may be coupled with the developing three-dimensional

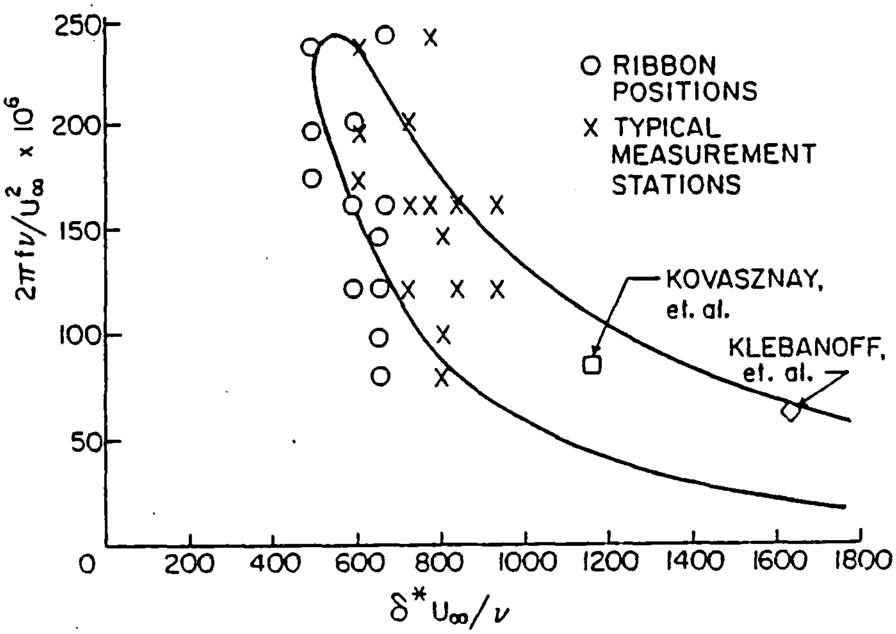

Fig. 1. Typical ribbon positions and measurement stations with respect to the stability diagram.

pattern found in the laminar boundary layer. Possible mechanism which may account for this coupling could be vortex amplification by stretching around the plate's leading edge or an instability mechansim associated with the stagnation flow leading to preferential spanwise growth. To study these possibilities, the spanwise variation of the rms velocity in the streamwise direction at $y/\delta = 0.2$ was measured for both leading edges with all other variables held constant. The results of these measurements are shown in figure 2. It is apparent that a similar spanwise structure developed quickly in both cases and persisted downstream. The pattern was consistent with the familiar counter-rotating vortex pairs shown by Klebanoff, Kovasznay, and others. Without the use of spanwise spaces, the "natural" pattern was somewhat irregular; however, a definite spanwise wavelength was found which was nearly the same for both leading edges. The pattern appeared to originate at or near the ribbon location. When the ribbon was turned off, no pattern was discerned. Likewise, velocity surveys upstream of the ribbon near the leading edge could discern no spanwise structure. The persistance of the pattern was remarkable, remaining through repeated plate cleanings and test modification. Over the course of the experiment, several ribbon replacements were necessary and each time the ribbon was changed the pattern showed slight shifts in its peak-and-valley position, but the average spanwise wavelength at a given longitudinal station remained unchanged. To investigate possible ribbon influence, the .002 x 0.60 in. (.05 mm x 1.5 mm) ribbon was replaced first with a thinner .001 in. (.025 mm) ribbon of the same width, and finally by a .005 in. (.13 mm) diameter tantalum wire. In both cases the detailed peak-and-valley pattern was slightly altered but the average spanwise wavelength remained the same. However, the amplitude pattern produced by the wire was more uniform across the span.

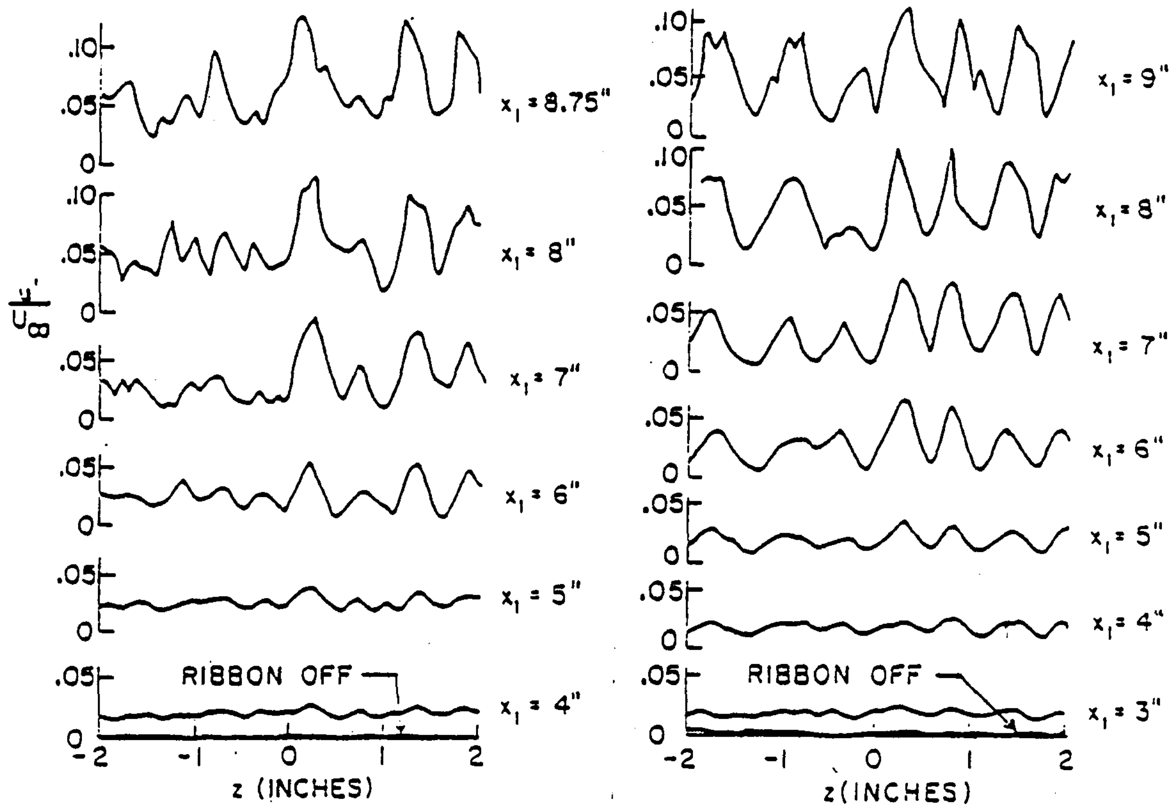

Fig. 2. Spanwise rms velocity patterns at $U_\infty = 35$ ft/sec with a 200 Hz ribbon frequency for the 0.25 in (left) and 2.0 in (right) leading edges.

The ribbon frequency was varied over the range $150 < f < 300$ Hz, corresponding to $80 < 2\pi f\nu/U_\infty^2 \times 10^6 < 240$ in figure 1, the wind tunnel free-stream velocity was varied over the range $15 < U_\infty < 45$ ft/sec and no significant changes in the spanwise wavelength occurred. The peak-and-valley structure was readily visable with no meaningful differences even when the ribbon was operating in the damped region, although the pattern decayed rapidly downstream.

A careful examination of figure 2 indicated that the spanwise wavelength for both leading edges increased slightly in the downstream direction. This was first felt to be a spurious result and considerable effort was expended to eliminate it. However, the trend persisted throughout the experiment over the entire range of the test conditions.

Figure 3 shows the variation of the average spanwise wavelength, λ , with longitudinal distance downstream from both leading edges. Although it is not always entirely clear as to what constitutes a bonafide peak/valley (see figure 2), the increasing trend is evident even with extremes in the pattern interpretation. The mechanism for this wavelength increase is not clear; however, it appears to be linked to the amplitude of the Tollmien-Schlichting waves. All the data reported here were taken at constant ribbon amplitude so that u'/U_∞ increased downstream with x_1. However, when the ribbon amplitude was decreased with increase-ing x_1 such that the u'/U_∞ amplitude was the same at each measuring station, a more pronounced increase of λ with x_1 was found. In addition, as breakdown was approached, the wavelength actually decreased in certain localized regions. This decrease may be the result of a second vortex structure that forms near breakdown on the high-speed sides of the original vortex pair as suggested by Klebanoff, et al. [1]. This effectively halves the wavelength locally. In the present

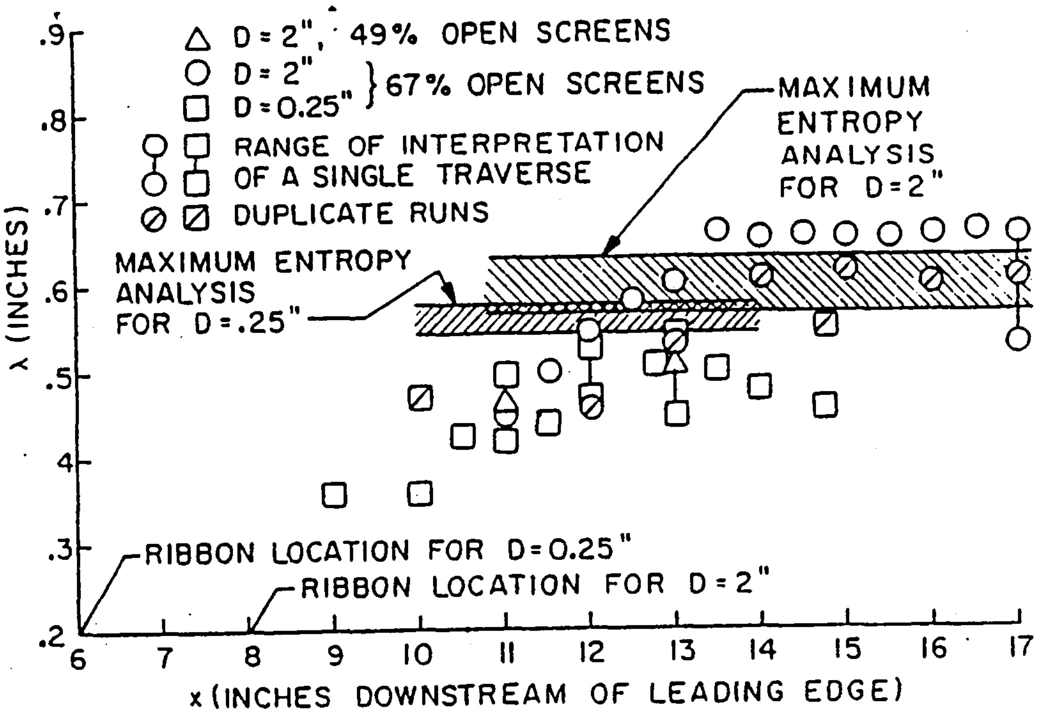

Fig. 3. Wavelengths at various frequencies at $y/\delta = 0.2$ and $U_\infty = 35$ ft/sec.

experiment, this usually occurred only for the central two or three vortex pairs where the ribbon amplitude was greatest.

The data of figure 2 were also studied using a maximum entropy spectral analysis technique originally due to Burg [5]. This method makes no specific assumptions about the continuation of the data outside the domain of interest and has been shown to be able to detect periodic trends embedded in noise. An algorithm developed by Andersen [6] was used to select the preferred wavelength in the data. This technique was not sensitive to the slightly smaller amplitude wavelengths seen near the ribbon and, thus, gave a nearly constant value of λ for the entire range of x as seen in figure 3. The slightly higher value of λ for D = 2.0 in. is probably not significant in view of the uncertainty in selecting the proper order of the filter for the technique.

As mentioned earlier, wind tunnel screens influence the spanwise pattern. To explore this effect on the present configuration, the two downstream screens in the settling chamber with 67% open area were temporarily exchanged for two screens of the same mesh size (20 x 20) but having only 49% open area. The detailed peak-and-valley structure was altered appreciably, but the spanwise wavelength remained essentially unchanged as seen by the two points plotted in figure 3. Similarly, removing the honeycomb upstream of the screens resulted in a sizable increase in the tunnel turbulence level but no appreciable change in the spanwise wavelength.

The experimental work of Klebanoff and Kovasznay utilized strips of cellophane tape on the plate surface to stabilize the developing three-dimensional structure so that it could be readily studied. To see that same effect in the present work, single strips of cellophane tape 0.175 in. (4.4 mm) wide by 0.50 in. (12.5 mm) long and spaced 0.35 in. (8.8 mm) apart were positioned on the plate surface just downstream of the ribbon. The 0.35 in. spacing approximately matched the "natural" wavelength measured at $x_1 = 3$ in. The resulting patterns in u' and $\bar{U}$ are shown in figure 4 for the larger leading edge and several different ribbon amplitudes. At the lower amplitude the mean and rms patterns are 180° out of phase, in agreement with the data of reference 1 and the present "uncontrolled" cases shown in figure 2 for $x_1 < 7''$. This portion of the developing spanwise structure has been modelled by Benney and Lin [7] and heuristically described by Blackwelder [8]. As the ribbon amplitude increased further the mean velocity maxima begin to develop local minima while the rms distribution remains unchanged. A further increase in ribbon amplitude caused the new minima to develop to the stage where the u' and $\bar{U}$ patterns were actually in phase with each other, at least over the central 2 in. (5 cm) of span. Breakdown for these data had not yet occurred, although the signals were highly non-linear (region B-C of reference 1). This new pattern may possibly by interpreted as due to additional, longitudinal vortex pairs forming on the high-speed sides of the original vortex pairs. However, since they have not yet altered the rms pattern, these new vortices may be different from the original pair. The discussion given by Klebanoff, et al. (see their figures 19 and 20) and the theoretical results of Benney [9] also show the formation of a new vortex pair in this region so the present data is not inconsistant with those findings. Further increases in ribbon amplitude and/or downstream distance resulted in breakdowns with new localized peaks forming in the old rms valleys (see $x_1 = 9''$ in figure 2). The remaining data were taken without the cellophane spacers.

In an effort to quantify the degree of nonlinearity and to establish the relationship of the evolving spanwise pattern to local breakdown,

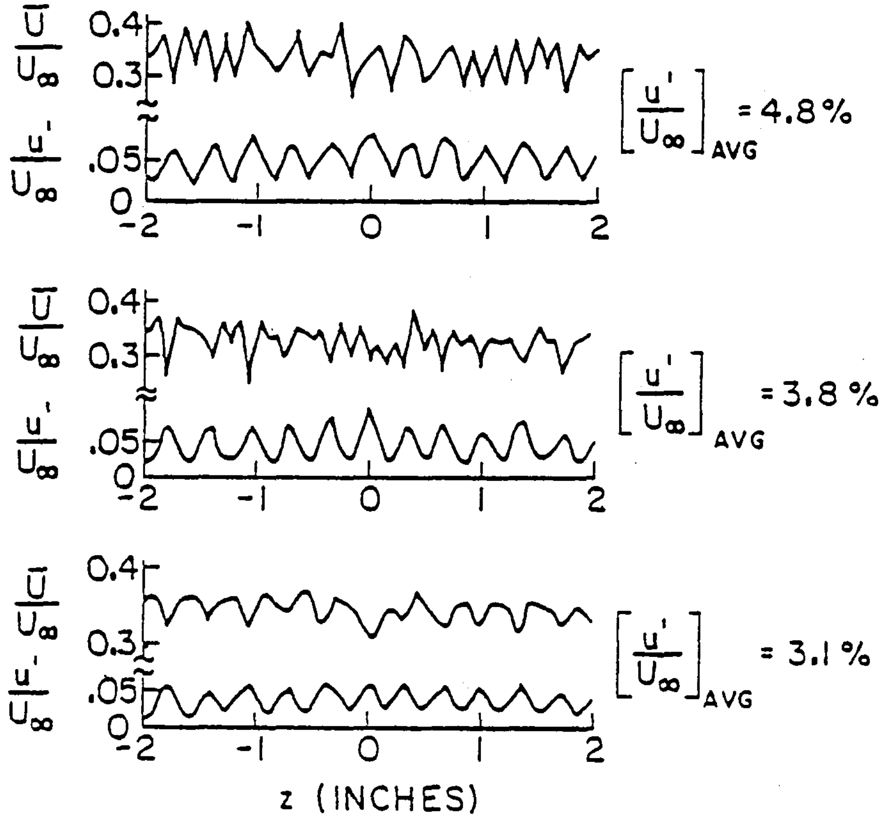

Fig. 4. Mean and rms streamwise velocity patterns at $y/\delta = 0.2$ and $x_1 = 3$ in. The spanwise average of the fluctuation is given at the right.

a spanwise rake was used at several downstream stations. The twelve wire output provided instantaneous spanwise velocity measurements at $y/\delta = 0.2$. The growth of an rms peak and valley are shown in figure 5. The departure from Tollmien-Schlichting growth rate of the peak and initial energy loss in the valley are apparently characteristic of the developing three dimensional structure. Local breakdown for this data occurred at $x_1 \cong 7.25''$. The corresponding spanwise patterns for this data are shown in figure 6. At $x_1 = 7''$, the mean and rms velocity patterns appear to be in phase as seen earlier at the higher amplitudes in figure 4. Upstream of $x_1 = 7.0''$, the mean velocity pattern is weak, although an rms peak is seen near the centerline, i.e., $z = 0$ for $x_1 = 6.5''$. Downstream of $x_1 = 7''$ the valley in the u' distribution develops into a strong peak as localized breakdown begins to occur on the centerline, similar to the new rms peaks appearing at $x_1 = 9''$ in figure 2. Possibly, the new vortex pairs forming in the nonlinear region do not make themselves felt in the rms distribution until at or after breakdown, but are easily detectable in the mean velocity distribution before breakdown.

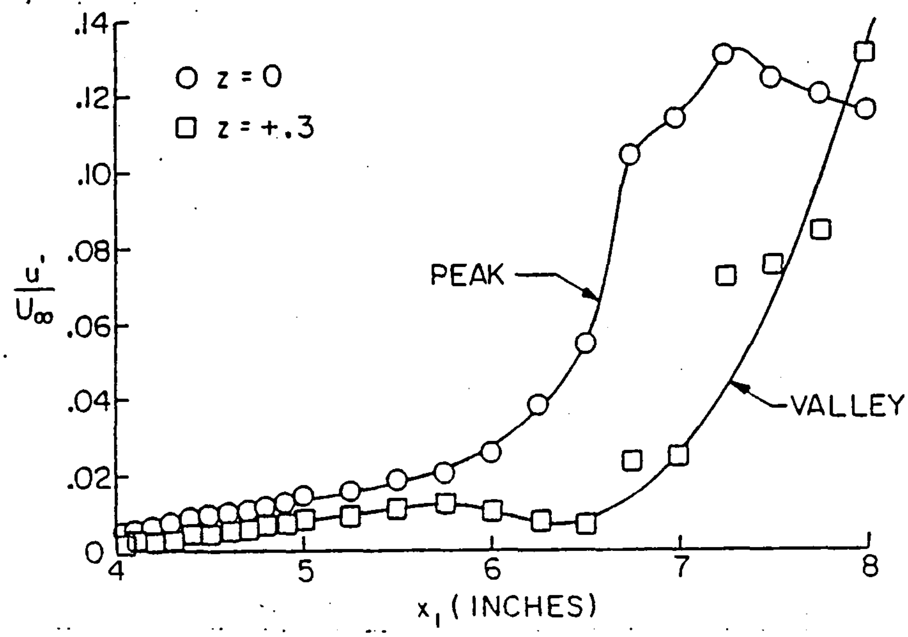

Fig. 5. Downstream development of a neighboring peak and valley from the simultaneous data of the spanwise rake. The z positions corresponds to those in figure 6.

The instantaneous hot-wire signals from the rake were cross-correlated with the ribbon input signal and the relative spanwise variation of phase angle at the ribbon frequency was obtained. This is also shown in figure 6 and the data indicate large spanwise changes in phase over relatively short distances.

Several spanwise traverses with the single hot-wire probe were made at various y/δ locations in the boundary layer. The results of one of these surveys at $x_1 = 6''$ are shown in figure 7. The relative spanwise variation of u' changes little through the boundary layer until $y/\delta = 0.55$ where an abrupt phase reversal of the spanwise pattern occurred. This reversal was found for both leading edges, with and without the tape strips. The only condition tested under which it did not occur was at high ribbon amplitudes. The phase change always

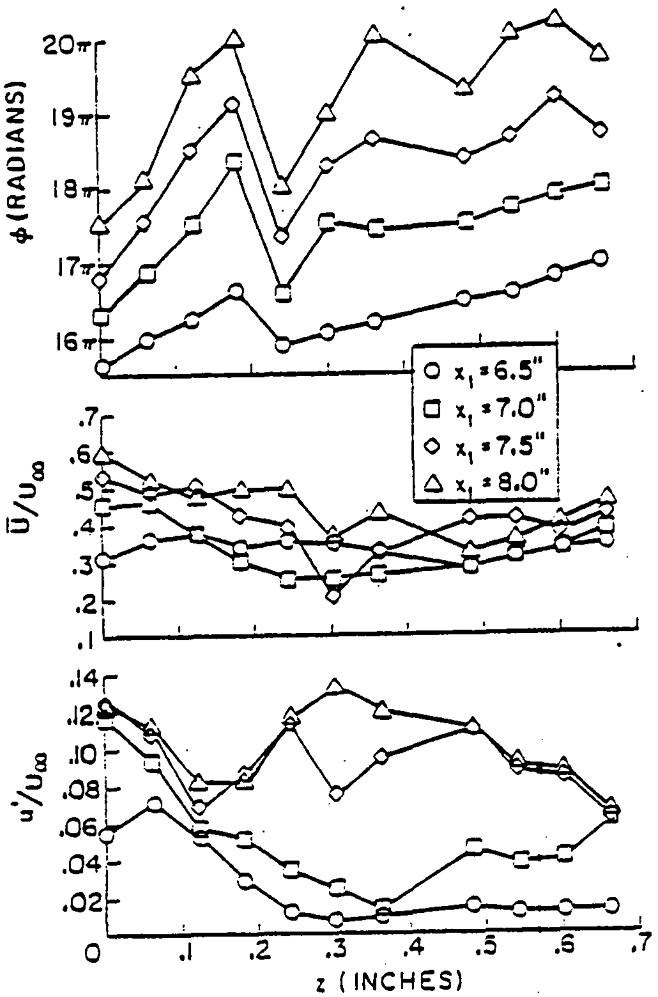

Fig. 6. Spanwise distribution of the streamwise velocity and its phase with respect to the vibrating ribbon at four downstream locations.

occurred near $y/\delta = 0.6$ where the familiar phase reversal of the Tollmien-Schlichting wave occurs. The implications of this interesting phenomena on the structure of the embedded vortices are not yet entirely clear. No corresponding phase reversal was found in the mean velocity pattern.

Concluding remarks

Several intersting conclusions may be drawn from the present study. First, a clearly definable, repeatable spanwise pattern in the longitudinal velocity existed in the present flat plate laminar boundary layer in both damped and undamped regions of the stability diagram for two-dimensional disturbances. The spanwise wavelength of this pattern was essentially invarient within the present test range of variables which included changing the settling chamber screen solidity (51%-33%), free-stream velocity (15-45 ft/sec), leading edge diameter (0.25-2.0 in) and ribbon frequency (150-300 Hz). The wavelength was found to increase slightly with streamwise distance to near breakdown where the apparent formation of new vortex pairs on the high-speed sides of the original pairs resulted in a spanwise wavelength halving. The mean, longitudinal velocity pattern showed these new vortices clearly before breakdown, but the rms pattern was not altered until local breakdown began to occur. A phase reversal of the spanwise rms pattern was noted above $y/\delta \cong 0.6$.

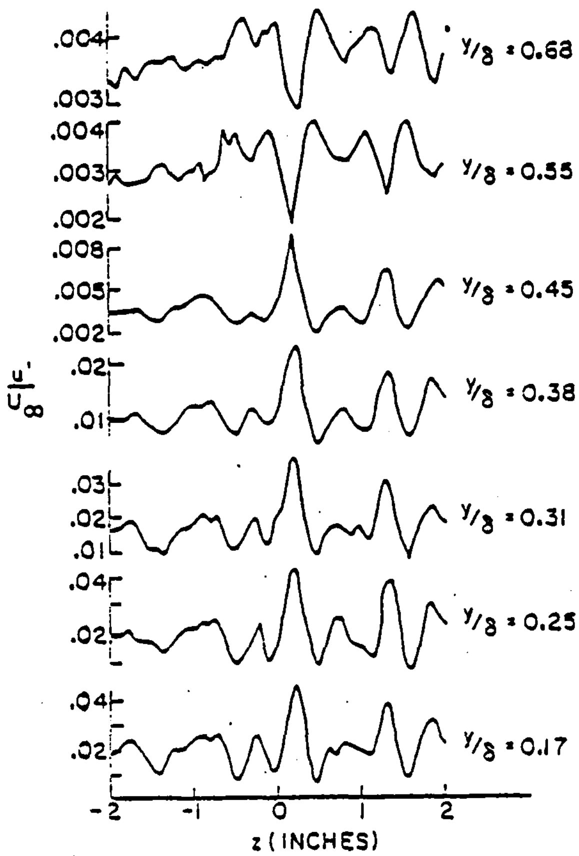

Fig. 7. Variation of the spanwise pattern with y/δ at $x_1 = 6$ in. with constant ribbon amplitude. Note the non-uniform scale on the ordinate.

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16. Abstract

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